

REPORT DOCUMENT

AD-A262 852

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing the instructions, searching existing data sources, gathering the data, reviewing the collected data, completing and reviewing the collection of information, sending the collection of information to the Washington Headquarters and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188).

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

February 1993

3. REPORT TYPE AND DATES COVERED

Professional Paper

4. TITLE AND SUBTITLE

AN OVERVIEW OF LOW FREQUENCY COMMUNICATIONS

6. AUTHOR(S)

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5. FUNDING NUMBERS

In-house Funding

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152-5001

8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152-5001

10. SPONSORING/MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. ABSTRACT (Maximum 200 words)

Use of Very Low Frequency and Low Frequency (VLF/LF, 3-300 kilohertz) electromagnetic signals for long range underwater communications predates World War II. VLF/LF communications is unique in that transmitted signals are transmitted over extremely long ranges and transmitting antennas are very large. Land-based antennas are typically designed to be supported by towers over 180 meters tall or to span mountain valleys. Airborne antennas typically measure seven kilometers long. Input powers of up to two megawatts provide detectable signals for megameters.

The development of this communications system has created and exploited numerous technical advances. Propagation research, material technology, numerical analysis and scale modeling, communications performance evaluation, and modulation advances will be discussed in the context of an overview of this worldwide communications system.

93 4 09 015

93-07473

Published in *Proceedings 92, Society of Women Engineers, Space Challenges: Earth and Beyond*, June 1992.

14. SUBJECT TERMS

Pseudo Atmospheric Noise Generator (PANG)
Real Time Channel Simulator (RTCS)
Coverage Prediction Workstation (CPWS)

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION
OF THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

SAME AS REPORT

UNCLASSIFIED

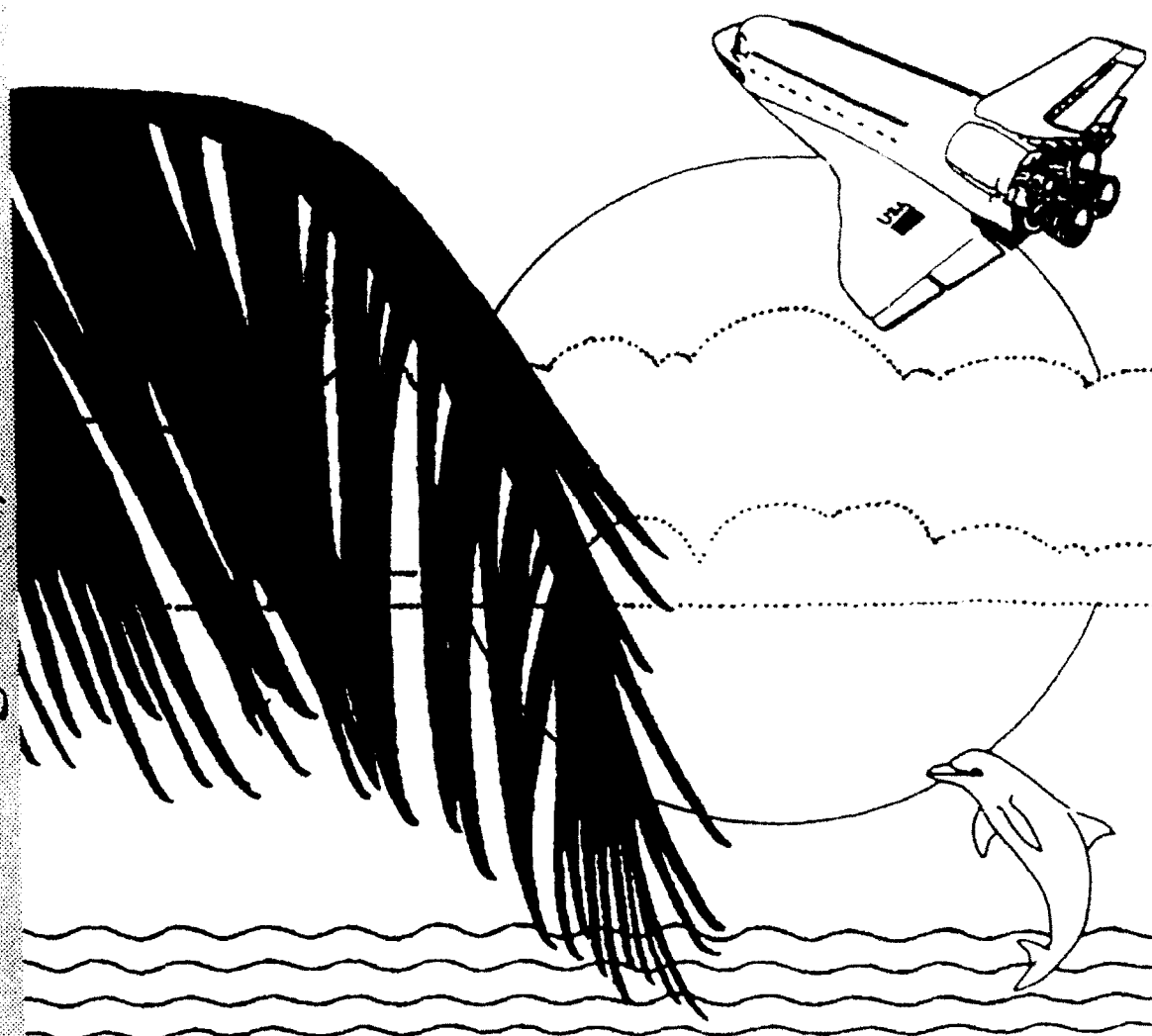
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proceedings

Society of Women Engineers

Space Challenges: Earth and Beyond

1992 SWE National Convention and Student Conference
June 22-27, 1992 - Orlando, Florida



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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>

AN OVERVIEW OF LOW FREQUENCY COMMUNICATIONS

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Availability Codes	
Dist	Avail and/or Special
A-1	20

ABSTRACT

Use of Very Low Frequency and Low Frequency (VLF/LF, 3-300 kilohertz) electromagnetic signals for long range underwater communications predates World War II. VLF/LF communications is unique in that transmitted signals are transmitted over extremely long ranges and transmitting antennas are very large. Land-based antennas are typically designed to be supported by towers over 180 meters tall or to span mountain valleys. Airborne antennas typically measure seven kilometers long. Input powers of up to two megawatts provide detectable signals for megameters.

The development of this communications system has created and exploited numerous technical advances. Propagation research, material technology, numerical analysis and scale modeling, communications performance evaluation, and modulation advances will be discussed in the context of an overview of this worldwide communications system.

LOW FREQUENCY PERSPECTIVE

VLF/LF communications occupies the 3-300 kilohertz band. Below are the power and telephone frequencies; and above are the commercial AM/FM and TV bands, and microwaves. Broadcast communications at and above the microwave frequencies are not efficient because the signal attenuates rapidly unless guided (as by fiber optics) or focused into a tight beam (as by lasers or dish antennas).

OPPORTUNITY AND CHALLENGE OF LOW FREQUENCY

The opportunity of low frequency is the ability to transmit a signal a long distance and below the surface. For a plane wave in a conducting media, such as air, signal strength attenuates exponentially with frequency: the lower the frequency the longer the communications ranges. The larger VLF systems are designed to communicate in the order of 10 megameters. VLF/LF also propagates well through sea water.

VLF and LF have applications beyond communications. VLF has been used for long range dissemination of precise standards of frequency and time for many years. Since 1960, the National Bureau of Standards has been transmitting standard time and frequency information at 20 kilohertz from their site in Colorado. The signal has been received as far away as New Zealand. VLF and LF are used for local and global navigation. The Omega navigation system is one example of an international navigation system. The low frequency capability to propagate into the earth has been used through the years to prospect for oil and to map subterranean features. Naturally occurring low frequency signatures have proven to be precursors of earthquakes.

There is great opportunity in the long range and subsurface propagation attributes of VLF and LF, and engineers have been exploiting this opportunity for nearly a century. They have also been dealing with the challenges of VLF and LF communications - low data rate, high power, and large transmitting antennas.

Data rate is proportional to frequency: the lower the frequency the lower the data rate. In addition, land-based antennas further restrict data rate because of their narrow bandwidth. Because of the strict data rate limitations, VLF and LF are not suited to voice or video data transmission. Not only is the data rate low, but VLF and LF communications require very high power to provide long range coverage from relatively inefficient antennas. Required powers are in the range of tens of kilowatts to megawatts at each transmitter site. A few bits of information transmitted at VLF and LF will travel far, but it is an expensive means of travel.

VLF antennas are physically large, with those for LF being somewhat smaller. However, because of the long wavelengths (up to 30 kilometers) in this frequency range, even the largest VLF and LF towers are electrically small. In general, both VLF and LF antennas have a vertical radiating section with top loading radials which add capacitance to make the antenna appear longer electrically. To reach efficiencies above 50%, towers can range from 150-300 meters with top hats areas greater than a square kilometer. In addition, an extensive ground plane of very low loss wires is needed to reduce losses from current flowing through the ground surface. These large structures and their associated transmitters and power amplifiers require large land area and millions of dollars to build, maintain, and operate.

Because of the challenge of low data rate, high power and large expensive antennas the "cost per bit" for VLF and LF communications is high. But even at this high cost, the opportunity inherent in long range and subsurface propagation at VLF and LF has kept engineers busy striving to overcome these challenges every since the days of Marconi.

HISTORY OF LOW FREQUENCY COMMUNICATIONS

Early transmissions used spark gap transmitters, which were modifications of the configuration used by Heinrich Hertz to detect electromagnetic waves. The first to realize that Hertz' electromagnetic waves could be used for signalling was Guglielmo Marconi, a young Italian electricity buff. He used trial and error to develop his idea, and on 2 June 1896, received English Patent #12039 - the first for wireless communication equipment. Marconi established the Marconi Company to make commercial use of his invention. The first international wireless station sent messages between England and France in 1899. In 1901, Marconi equipment sent the first trans-Atlantic signals from Poldhu in Cornwall, England, to an antenna held aloft by kites and balloons in Newfoundland, Canada. The frequency of first radio transmissions across the Atlantic are unknown because the cymometer, which measures frequency, was not invented until 1904.

Once Marconi demonstrated the feasibility of his invention, other commercial companies built on his work. In 1901, there was both unintentional and intentional interference between radio stations in New York harbor. This was when the Marconi Company, the American Wireless Telephone and Telegraph Company, and the De Forest Company all tried to report the International Yacht Races at the same time. That was probably the first marked case of radio interference and the first radio jamming fight in this country.

The early impetus for long range "wireless" communications came from the needs of the various colonial empires, desires for transoceanic communications services and the command and control needs of the various navies. For many years, wireless communications meant low frequency. The first commercial Atlantic service (begun in 1907 between Glace Bay, Newfoundland, Canada and Clifden, Ireland) was at 82 kilohertz, in the low frequency band. Between 1910 and 1912, a number of commercial operations used frequencies of 12-13 kilohertz for long range communications.

Between World War I and World War II, VLF and LF transmissions fell into commercial disuse as improvements in high frequency techniques made HF communications commercially feasible. However, VLF and LF networks continued to be used by those whose need for highly reliable long range communications could be balanced by their greater cost.

In 1941, the Goliath station at Kalbe, Germany began transmitting 1000 kilowatts at 16.5 kilohertz. The station was well named, with eighteen masts ranging from 175-200 meters tall. The top hat was 1.25 square kilometers, which is more than 280 football fields. Despite having a ground system of galvanized iron rather than copper, the

final antenna had an efficiency of nearly 50% at its lowest operating frequency. This efficiency is twice what had previously been accomplished. After World War II, the Russians moved the Goliath station to Gorki, Russia. Subsequently, more large VLF stations and antennas were built to provide worldwide coverage of the military message traffic required during and after WWII. They used larger top hats and more powerful transmitters. When the U.S. Naval Radio Transmitting Facility at Cutler, Maine, was built in 1961, the signal could literally be "heard around the world."

Airborne VLF and LF transmissions began in the early 1960's. The antenna trailed by an airplane flying at five kilometers can be more than seven kilometers long. Long antennas are more efficient than shorter ones and, for air to surface communication, are most effective when oriented vertically. To optimize this verticality, the antenna is formed into a corkscrew shape behind and below the airplane. The tight spiral turn the airplane must maintain to meet that criteria is physically demanding on airplane and crew alike.

Although new VLF/LF transmitting sites are being built, many of the early sites are still operating due to the heavy investments made in them. For example, the VLF transmitting site at Annapolis, Md was constructed in 1918 and was modified in 1922 and 1941. These sites and the VLF/LF communications system have withstood the many modifications dictated by advancing technology and changing communications requirements. This is a testimony to the opportunities of LF communications.

TECHNOLOGY ADVANCES TO MEET THE CHALLENGES OF LOW FREQUENCY

The need to employ the unique benefits of low frequency communications has provided the impetus to exploit and create technology advances to overcome its challenges.

Propagation Research: VLF/LF signal strength does not decrease monotonically with distance from the transmitter, but shows alternating maxima and minima as distance increases. The location of the maxima and minima is a function of time, location, and frequency. For any given transmission path, the signal strength changes with the state of the ionosphere, which in turn is a function of time of day, season of the year, and even the sunspot cycle.

Radiated signals are measured to validate performance and to validate propagation prediction programs. Twenty years ago engineers slaved over paper tape print outs to glean a few precious signal data points. Today, VLF/LF receivers are gathering data worldwide and providing an avalanche of data on computer disk. Now the challenge is to quickly cull the questionable data and to develop automatic processing routines for the remainder.

The predominant atmospheric noise at VLF/LF is generated by lightning storms. This noise propagates and is affected by the ionosphere in the same manner as the VLF/LF signal. Noise measurements are being performed worldwide to improve existing noise models. Research is ongoing in location and frequency of lightning strikes and on detailed characteristics of lightning.

Material Technology: When the power into a typical VLF/LF antenna is increased, the voltage limit of one of the antenna components will eventually be exceeded. At this point the component will go into corona. This is a flow of current between the component and ground which wastes energy and is potentially harmful to the antenna component. Advances in material technology have significantly increased the power handling capability of the transmitting antennas.

Currently base insulators and bushings utilize conventional porcelain. The practice of using porcelain insulators developed for the power industry has led to designs which are not optimized for LF communications and which require a long lead time for fabrication. To cope with these shortcomings, the Naval Civil Engineering Laboratory in Port Hueneme, California has developed a new composite material called Polymer Concrete. The advantages are: fabrication at the construction site; flexible size and shape; curing time of less than a day; and repairable on site. Weathering tests and investigations into protective coatings are ongoing.

Another material being applied to LF applications is Metglass, an amorphous solid that has low loss properties which are ideal for transformer applications. Until recently, the choice of low loss core materials was limited to ferrite; now Metglass is available with equally low core loss at frequencies below 200 kilohertz. The maximum flux density for ferrite is 3000 gauss, and for Metglass is 15000 gauss. Since the reactive volt-amperes rating of a component is directly related to the square of the flux density, it follows that for a given volt-ampere rating the metglass transformer is only one twenty-fifth the size of the ferrite transformer for equal ratings.

Antenna Numerical Analysis and Scale Modeling: The large size of VLF and LF antennas makes design by trial and error prohibitively expensive; the complexity of the electromagnetic equations makes analytical approaches prohibitively time consuming. Two methods which have been developed to aid VLF/LF antenna engineers are numerical electromagnetic computer codes and physical brass scale models.

Most of the numerical codes developed to model antennas were originally designed for higher frequency applications. Applying these codes at VLF creates problems. For example, values that are very small but significant at VLF are treated as acceptable error by an HF code. New techniques are being developed for VLF applications. Currently, some of the simpler LF antennas can be modeled using PC's. Ongoing investigations into the use of new techniques promise greater accuracy and increased modeling speed.

Brass scale models of VLF and LF antennas have advanced techniques developed originally for HF shipboard antenna design. During the past 5 years, VLF antennas have been modeled at scales as small as 1800:1. The wires used in these models are less than the diameter of a human hair. These models have proven amazingly accurate, and in addition to their usefulness as an electrical model, they also provide visual reference for mechanical engineers and maintenance personnel.

Communications Performance Evaluation: As the VLF/LF communications systems grew more important and more extensive, it became necessary to develop system evaluation and development tools. Three of these tools are the Pseudo Atmospheric Noise Generator (PANG), the Real Time Channel Simulator (RTCS) and the Coverage Prediction Workstation (CPWS).

PANG is a simulated atmospheric noise source. It has become an international standard for evaluating the performance of VLF/LF receivers. PANG generates a signal which emulates the signal spikes of nearby lightning strikes and the background Gaussian noise of distant storms. Early versions used actual recording of atmospheric noise which were of limited length; now the noise is being simulated by computer control which is more flexible. Simulation of real noise dynamic ranges of up to 90 dB continues to be a challenge.

The RTCS simulates the overall signal environment. It takes a signal transmitted by a laboratory receiver, attenuates and distorts it to match a desired propagation scenario, adds atmospheric noise (PANG) or other noise sources, and presents a "real" signal to the laboratory receiver. Since the upgrade from mechanical switches to computer control, the RTCS can simulate any environmental effect that can be described.

The CPWS predicts propagated signal strength versus distance. Signal levels are calculated as modal solutions to the earth ionosphere waveguide. The waveguide calculations must consider variation of ionosphere profile, orientation of the geomagnetic field and ground conductivity. Atmospheric noise models are also included in the program. Simulations which took a week to develop in the laboratory five years ago will soon be produced on a PC overnight. Communicators will use these expert systems as a tool to support daily broadcast management.

Modulation Techniques: Early signalling used International Morse Code. Dots and dashes were periods of constant amplitude delineated by periods of no signal. A transmission rate of 10-20 words per minute required 14-28 keying cycles per second. This simple binary system was replaced by other forms of modulation.

Modern methods of transmitting binary information are Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). FSK uses two different frequencies of the carrier to send binary signals. One frequency represents the binary "1" and the other frequency represents the binary "0". PSK uses the two opposite phases of a basic sinusoid (the carrier) to indicate the two possible states. PSK is more efficient than FSK, but cannot be used for VLF/LF

because the instantaneous phase shifts create high voltage transients that would destroy transmitter output circuits. Minimum Shift Keying (MSK) is the current modulation scheme of choice. In MSK the frequency stays constant when the bits are constant (all 1's or 0's); the frequency shifts when the next bit is different (1 changes to 0 or 0 changes to 1).

Although VLF/LF communications are basically reliable, signals do attenuate and suffer phase shift. Thus, error protection is often used to ensure that the signal received is that which was transmitted. Redundant digits are added to the transmitted message according to a specific algorithm. At the receive end, the redundant digits are stripped and recalculated using the same algorithm on the received message. If both are the same, the message is considered error free. Certain algorithms provide both error detection and error correction capability.

Data compression techniques have been studied to improve the effective data rate of VLF and LF transmissions. One method is to encode the data such that a certain transmitted group of characters is decoded to a larger phrase or sentence. This works well if transmissions are limited to specific topics or statements; but it is not effective for general transmissions. A more general compression technique is to code the alphabet so that the most frequently used letters require the fewest bits.

Paradoxically, the low data rate feature of LF communications encourages state of the art modulation and error correction techniques. The high ratio of computer speed to data rate allows powerful processors to effectively perform advanced and complex signal processing techniques in real time. Techniques developed at LF can be transferred to higher frequencies as computers increase in speed.

CONCLUSION

The propagation characteristics of LF and VLF provide the opportunity of worldwide and subsurface broadcast. The challenges of VLF and LF communications are high power, large transmitting antennas and low data rate. The need to employ the unique benefits of low frequency communications has provided the impetus to exploit and create technology advances to overcome these challenges.

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ACKNOWLEDGEMENTS

We wish to acknowledge our colleagues for their input and review. Thank you to Jim Brooks of the Naval Civil Engineering laboratory, and W. Roger Dishong, Dr. Jerry Ferguson, Gerry Hudnall, Ingvor Inaneci, Leo Johnson, Jim Logan, Tom Schlosser, Jim Schukantz, Paul Singer, and Bob Williams all of Naval Command, Control and Ocean Surveillance Center RDT&E Division.